RESEARCH DEPARTMENT

Derivation of colour scanner analysis characteristics to give optimum reproduction of cine film without matrixing

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RESEARCH DEPARTMENT

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SUMMARY

This report describes computations made to determine the shape of the positive-only colour scanner analysis characteristics which give the optimum reproduction of colours produced by film dyes. Due regard was paid to the difficulties of instrumentation and to the necessity of achieving a good signal-to-noise ratio. It is estimated that use of the characteristics determined will effect a substantial improvement in the performance of certain scanners at present in use.

1. INTRODUCTION

1.1. Colour Analysis

A theoretical relationship exists[1] between the chromaticities of the primaries used in additive colour synthesis and the spectral sensitivity characteristics of the three receptors by means of which the signals controlling the primaries are produced. Fig. 1 shows the analysis characteristics ideally suited to the standard NTSC display primaries. If the analysis characteristics of a television pick-up device conformed to those shown in Fig. 1, the result would be perfect reproduction of every colour, subject to the limitation that the display phosphors are not capable of producing negative light. That is all colours whose chromaticities lie within the triangle formed by joining the chromaticities of the display primaries would be reproduced at their original chromaticity and correct relative luminance.* Colours lying outside the triangle would in theory require a negative contribution from either one or two of the phosphors for correct reproduction. How-

* Relative to white (for example).

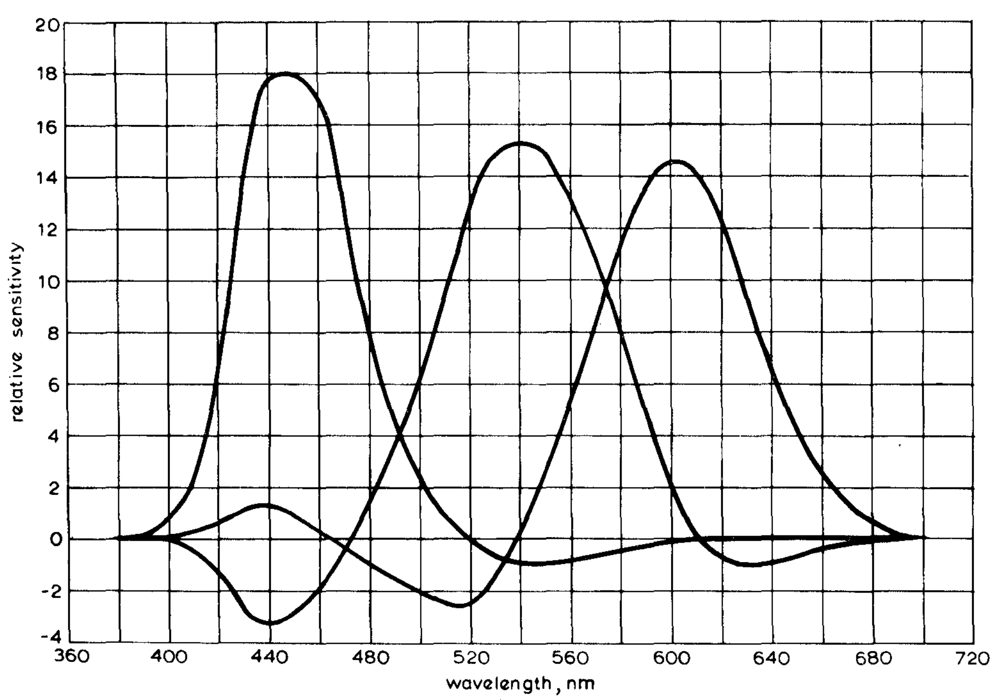

Fig. 1 - Ideal analysis characteristics for NTSC primaries. Equi-energy normalised

ever, in practice such contributions are not possible, the phosphors required to make them would in fact emit no light, and the reproduced colour would have a chromaticity lying either on the edge of the triangle whose apices are the chromaticities of the display primaries or at one of the apices. The reproduced luminance of such colours would be higher than the proper value.

Such reproduction is not at present achieved, because methods of realising the negative lobes shown in Fig. 1 have not yet been adopted. Analysis characteristics which are entirely positive will in general give errors in reproduction even of colours whose chromaticities lie within the display triangle. Positive-only analysis characteristics giving the optimum reproduction of a range of natural colours have been computed, and form part of the colour camera Specifications TV/126 and TV/148.

Analysis characteristics such as those shown in Fig. 1 are known as colour mixture curves, and may be obtained by adding suitable proportions of the CIE distribution functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$. These functions are everywhere positive, and it is therefore possible to use them, or a set of positive-only combinations of them as the basis for analysis and then to obtain the signals appropriate to the NTSC primaries by a matrix procedure. This would be equivalent to using the analysis of Fig. 1 and would therefore result in perfect colour reproduction. However, matrixing decreases the signal-to-noise ratio, and so the original analysis would need to be chosen in such a way that the outputs of the receptors had signal-to-noise ratios in excess of those required for the final signal. Such combinations of analysis and matrixing were not considered in the work to be described. The technique is, however, being investigated, and results obtained so far[2] indicate that it is likely that an advantage will accrue from its use.

1.2. Colours Portrayed by the Film

When a colour film is optically projected, the colours are normally produced by a subtractive process, the light passing through the film being modified in spectral composition by the selective transmission of three superimposed dye layers. By adjusting the concentrations of the three dyes, one may obtain colours of almost any required chromaticity. However, the relative luminances of such colours are very much lower than those theoretically obtainable,[3] and somewhat lower than those of certain artificially produced colours (for instance the EBU Courtauld Fabric colours lie just on or else inside the gamut of Eastman film dyes, whereas the bright and saturated colours used in the BBC Colour Camera Test Light Box lie outside the Eastman gamut).

Moreover, only one combination of dye concentrations can be used to synthesize a given chromaticity and luminance. Thus any given film colour can have only one spectral composition. Natural colours having equal chromaticities and luminances for a given illuminant, on the other hand, may be produced by a wide range of spectral compositions (such colours are termed "metameric").

Thus film colours are limited, both in gamut and in spectral composition, as compared with natural colours. It therefore seems reasonable to suppose that the set of analysis characteristics required for the optimum reproduction of film colours might be different from those required for the optimum reproduction of natural colours. Moreover once an appropriate choice of characteristics is made, it should be possible to reproduce the limited range of film colours more accurately than the much more extensive range of natural colours.

It may be possible to use matrixing methods to increase the range of colours obtainable from televised cine film. However, the analysis to be described did not envisage the use of such a technique, in fact it was assumed that the colours observed when the film is optically projected are those which the producer intended the viewer to see.

2. DETERMINATION OF OPTIMUM CHARACTERISTICS

The colour gamuts of Eastman, Technicolor and Gevaert colour dye sets were computed assuming Illuminant C.* Thirteen colours were then chosen from each gamut. One of each set was a neutral giving 10% transmission. The other twelve covered the range of chromaticities most likely to be encountered in practice, and each had the maximum luminance obtainable from the film. It was thought that an analysis which gave satisfactory reproduction of these thirteen colours would give satisfactory reproduction of the whole film gamut. The analysis of each film was then considered separately, and two procedures were used. The first will be described only briefly, since it produced analysis characteristics that were considered to be impracticable.

2.1. Procedure No. 1

Analysis characteristics were synthesized by application of the least squares technique[4] to a series of equations relating the signal voltages obtained by analysis of the test colours to those necessary for accurate reproduction of the colours.

* A report describing in detail this part of the work is being prepared, but briefly the technique was to measure the spectral densities of samples of the three film dyes, and then to explore the range of chromaticities and luminances that could be obtained by choosing any two of the three dyes and combining them in varying concentrations.

The solutions were modified* so as to ensure that the resulting characteristics were smooth curves, being everywhere positive, and having only one peak. Such restrictions involved a departure from the least-squares condition, but this was arranged to be as small as possible.

* The author is grateful to Mr. J.W. Head who was responsible for this part of the calculation.

2.2. Procedure No. 2

This procedure was essentially one of analysis rather than synthesis and was practicable only because of the availability of a computer.

Ten feasible optical characteristics, identified in Fig. 2 by the numbers 0 - 9, were tried for each channel. Thus any one of the given curves (0 to 9)

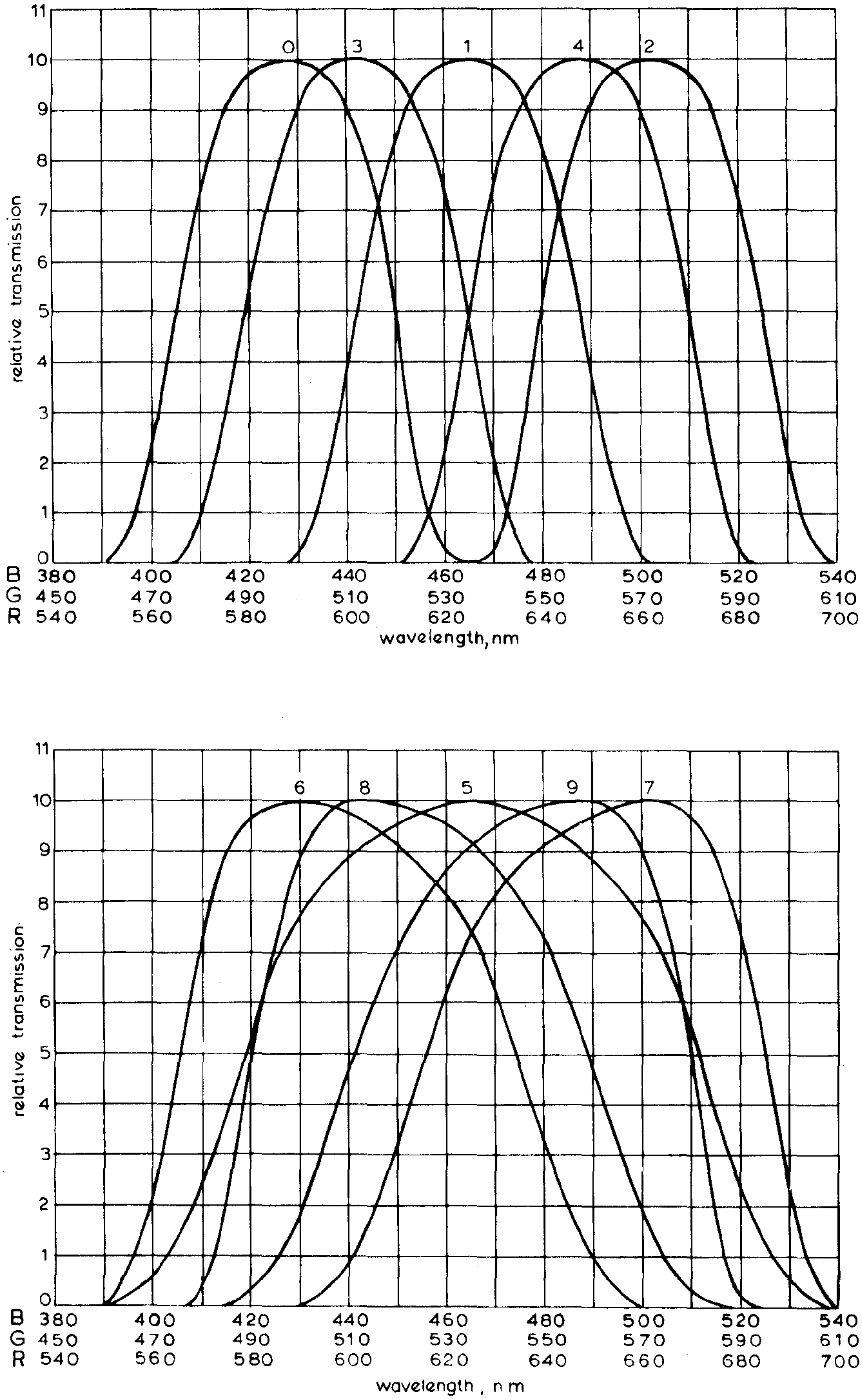

Fig. 2 - Transmission characteristics tested

could be used for any one of the three channels, or for that matter, for two or all three of the channels, if required. The three wavelength scales shown in the figure relate to the appropriate channels, as indicated. These curves are the assumed spectral responses of a fictitious set of dichroic filters and shaping filters. They were chosen to cover a wide range of wavelengths, and to have shapes which were thought to be easily achieved by available optical elements. Each optical characteristic was multiplied by the product (shown in Fig. 3) of the spectral characteristics corresponding to the emission of the cathode-ray tube and the sensitivity of the photo-multiplier to give ten feasible overall analysis characteristics for each channel.

These analysis characteristics were first normalized so that the areas under the curves were all equal. This ensured that every combination of one blue, one green and one red unit would produce equal B, G and R signals when the colour analysed corresponded to a neutral of equal transmission at all wavelengths. Actually the neutral corresponding to white on the film is somewhat frequency selective but it was thought that any subsequent unbalance of signals due to this would be small. A total of 1000 different combinations of red, green and blue analysis characteristics was possible, and the performance of each of these in turn was examined.

Each of the thirteen film colours was analysed by the combination under investigation. B, G and R, the integrated products of the spectral transmittance corresponding to a given colour and the blue, green, and red overall analysis characteristics respectively, were computed. A "3 × 3" matrix then enabled the chromaticity and relative luminance of the colour as reproduced using NTSC primaries, to be obtained.

Reference was then made to the chromaticities and relative luminances of the colours which would have been obtained from the film by optical projection using an Illuminant C. Errors of reproduction introduced by the telecine process were calculated, and expressed in just noticeable difference (jnd)* units. The following empirical relationships between calculated differences in reproduction and jnd units were assumed:

the number n_c of jnds of chromaticity error is given by:

$$n_c = [(u_o - u_r)^2 + (v_o - v_r)^2]^{\frac{1}{2}} / 0{\cdot}00384$$

where (u_o, v_o) and (u_r, v_r) are the chromaticities of the original and reproduced colours expressed in terms of the 1960 CIE-UCS (uniform chromaticity scale) diagram.

* 1 jnd unit defines a difference which is just apparent to the average observer.

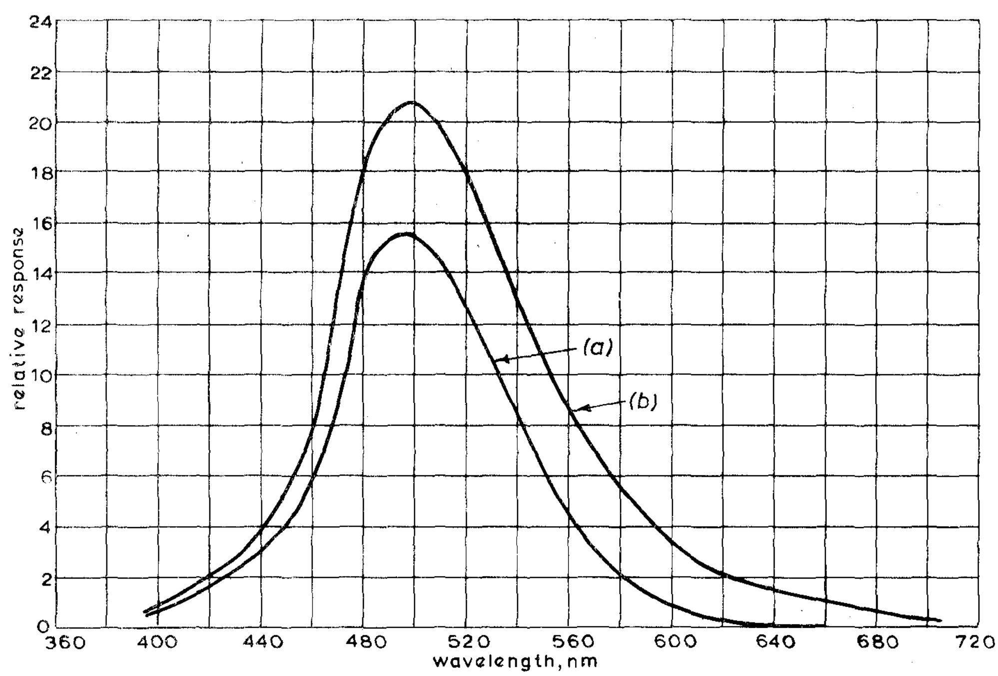

Fig. 3 - Combined responses of cathode-ray tube and photomultipliers

(a) blue and green channels (b) red channel

The number n_L of jnds of luminance error is given** by:

$$\frac{L_r}{L_o} = (1{\cdot}02)^{n_L}$$

i.e. $$n_L = \frac{\log L_r - \log L_o}{\log 1{\cdot}02}$$

where L_o and L_r are the relative luminances of the original and reproduced colours.

The number n of jnds of colour error produced by the simultaneous presence of chromaticity and luminance errors may be taken as:

$$n = (n_c{}^2 + n_L{}^2)^{1/2} \quad ***$$

The root mean square of the errors n relating to all thirteen of the test colours was determined, this quantity being regarded as a measure of the accuracy of reproduction attainable using the analysis combination in question.

In the initial stage of the calculation, the computer was arranged to print out the r.m.s. colour error figures against a number which identified the analysis combination investigated. It was also arranged to store in order of merit the identification numbers of the twenty combinations which gave lowest r.m.s. errors. The calculation was then repeated for each of these twenty combinations; this time figures relating to the chromaticity and luminance errors of each colour analysed were printed out. This was done because it was considered desirable to choose an analysis which not only gave a low r.m.s. colour error but which also ensured that no one colour would be very badly reproduced.

The whole procedure was carried out three times, using Eastman, Technicolor and Gevaert film dye data.

It was observed that several analysis combinations featured in the lists of the twenty best for all three types of film, moreover the combination identified by Fig. 2 as No. 6 (blue), 4 (green), 8 (red) was found at the head of each list. This combination, together with three others was examined in still greater detail to ascertain the directions in which shifts of chromaticity were made, combination 6.4.8. being finally chosen as the optimum set of analysis characteristics.*

** This is an expression of the Weber-Fechner Law[5], the Fechner fraction $\Delta L/L$ being assumed to be constant at 2% over the range of luminances considered.

*** It is realised that these expressions give only an approximate measure of the subjective impression produced by colour errors. Nevertheless they were regarded as being sufficiently accurate to enable a meaningful assessment of the performance of the proposed analysis characteristics to be made.

3. DISCUSSION OF RESULTS

The two procedures described involved the use of quite different criteria - viz. minimum values of sums of squares of errors for procedure No. 1 and minimum values of combined luminance and chromaticity jnds for procedure No. 2 - and were quite independent in their derivation of optimum analysis characteristics from the original data. Nevertheless the analyses thus derived were found to be nearly equivalent from a colorimetric viewpoint, since almost exactly the same r.m.s. colour error (defined in jnd terms) would result from the use of either set. However, procedure No. 1 did not incorporate requirements respecting ease of instrumentation and signal-to-noise performance; the resulting characteristics would be difficult to instrument and would involve a loss of signal-to-noise ratio of about 4 dB as compared with those resulting from procedure No. 2 (assuming equal peak efficiencies in each optical path considered separately).

The characteristics derived using procedure No. 2 are therefore regarded as optimum. They are plotted in Fig. 4, and Figs. 5, 6 and 7 show how the 39 test colours would be reproduced by them.

4. COMPARISON WITH EXISTING SCANNERS

It was thought desirable to assess the degree of improvement which could be expected to result from the use of the optimum analysis characteristics. The reproductions of two existing scanners, one at Research Department, the other an operational machine situated at Lime Grove, were therefore calculated using their measured analysis characteristics. It was found that the r.m.s. colour error (jnds) of the Research Department machine could be reduced by a factor of almost 3 : 1, and that of the operational machine by about 2 : 1, if the optimum analysis were substituted for their present analyses.

In order to assess the relative noise performance, it is necessary to know not only the shapes of the analysis characteristics but also the peak transmissions of the optical system. It was estimated that in instrumenting the optimum analysis it

* The procedure described in Section 2.2 was repeated for sulphide instead of NTSC display phosphors, and combination 6.4.8. was again found to be the optimum. This time errors of reproduction were greater, since these primaries are more restricted colorimetrically and demand ideal analysis characteristics having larger negative lobes.

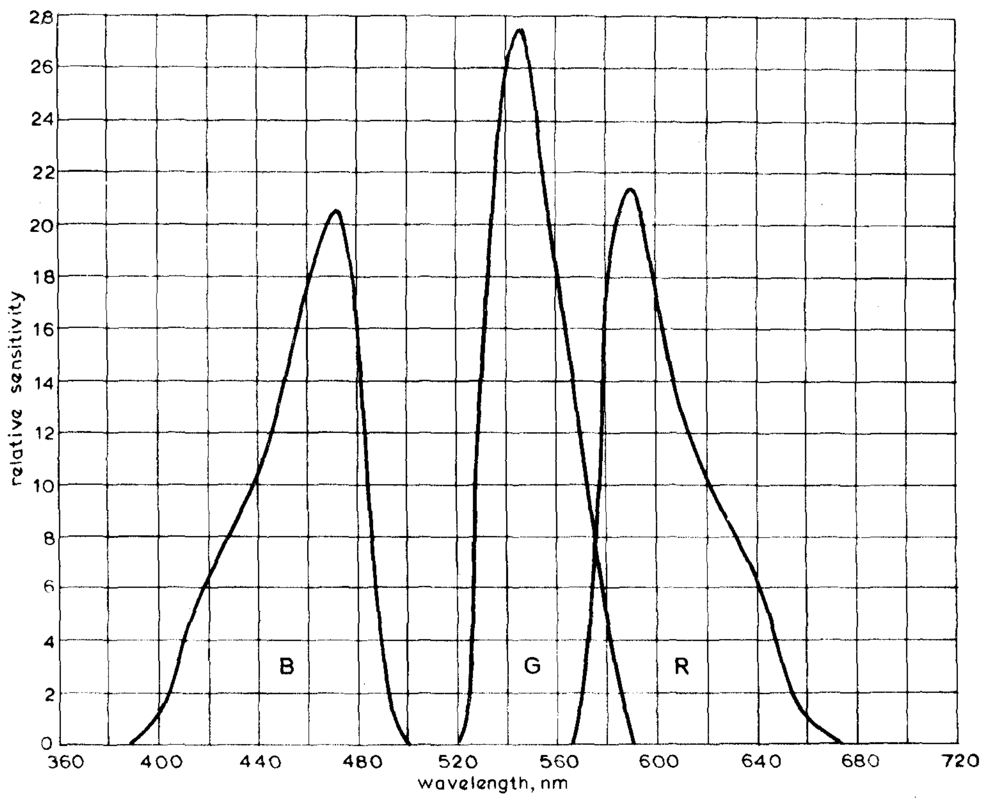

Fig. 4 - Optimum positive-only scanner analysis characteristics. Equi-energy normalised

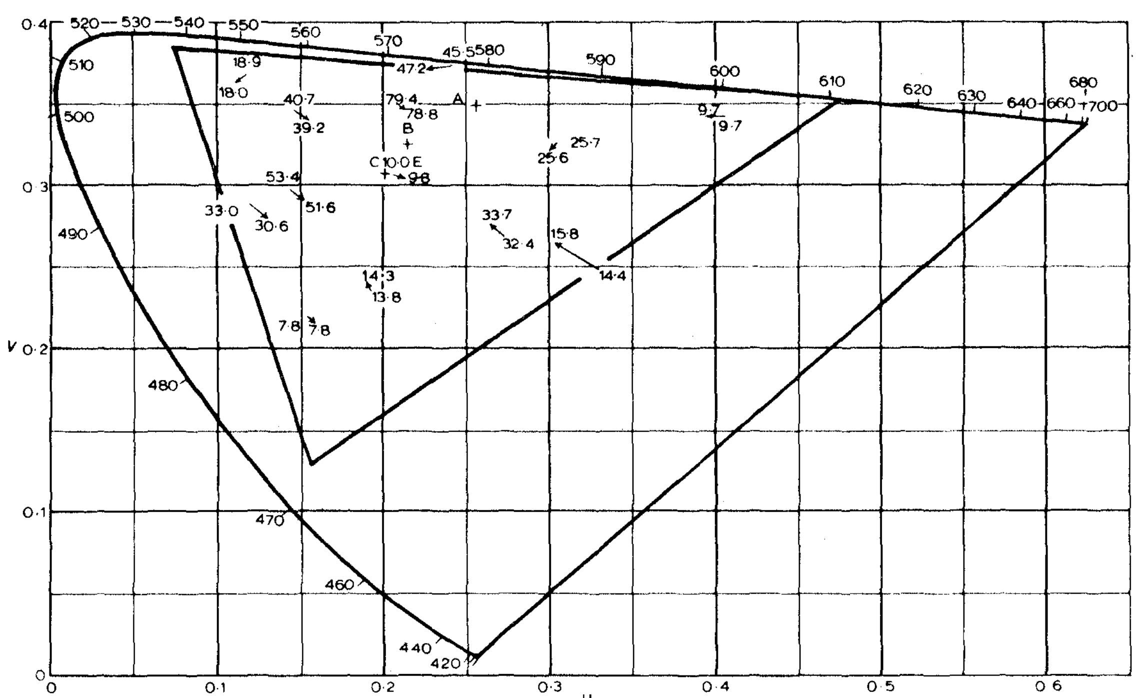

Fig. 5 - Eastman film test colours as viewed by Illuminant C and as reproduced using analysis combination No. 6.4.8. Reproduced colours at arrow heads. Figures are luminous transmittances expressed as percentages. r.m.s. colour error = 3·5 jnd

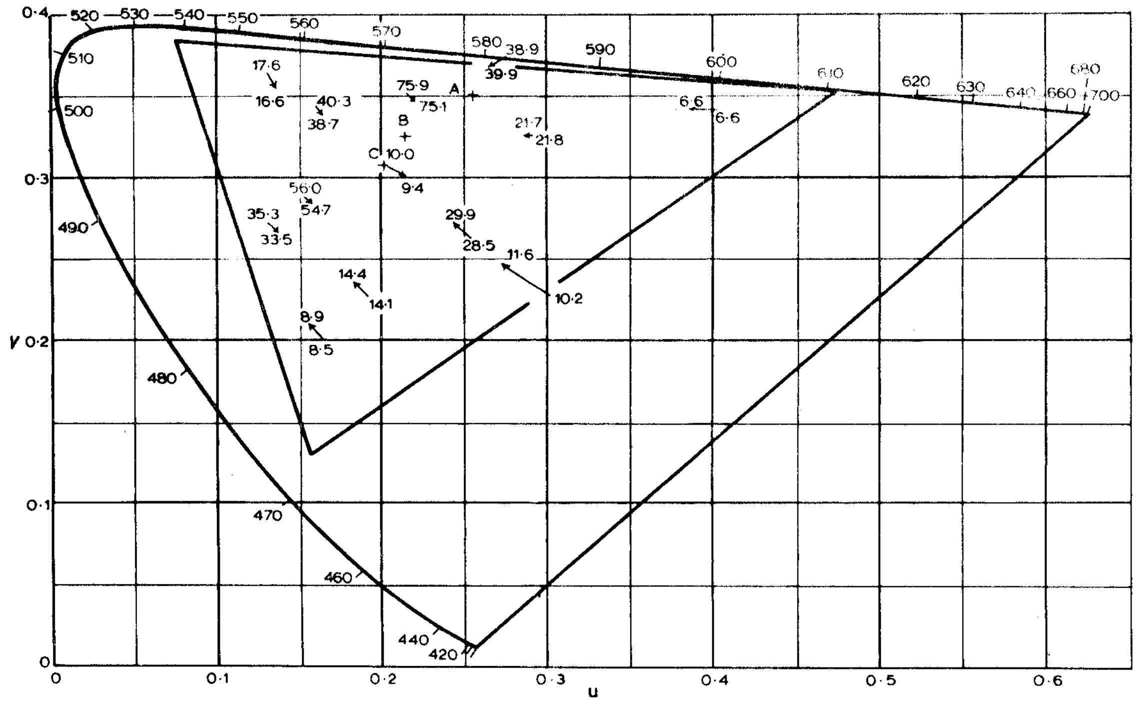

Fig. 6 - Technicolor film test colours as viewed by Illuminant C and as reproduced using analysis combination No. 6.4.8. Reproduced colours at arrow heads. r.m.s. colour error = 4·6 jnd

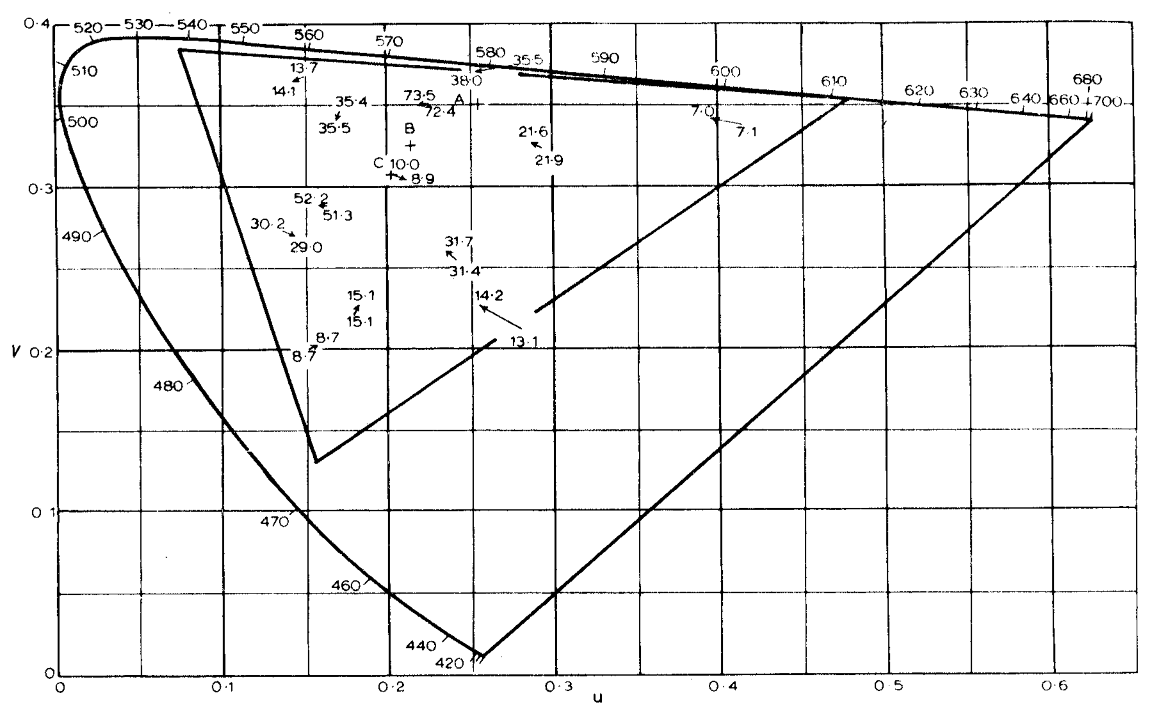

Fig. 7 - Gevaert film test colours as viewed by Illuminant C and as reproduced using analysis combination No. 6.4.8. Reproduced colours at arrow heads. r.m.s. colour error = 4·2 jnd

would not be difficult to achieve peak transmissions approximately equal to those which obtain in the Research Department scanner. On this basis, it was calculated that the improvement in colour rendering would be achieved in exchange for a loss of about 1½ dB of signal-to-noise ratio as compared with that obtained using the Research Department machine.

5. CONCLUSIONS

Two independent procedures have been used to obtain positive-only colour scanner characteristics giving optimum reproduction of the colours produced by cine-film. The two sets of characteristics obtained are virtually equivalent in terms of accuracy of reproduction. One set however has a substantial advantage in instrumentation and noise performance, and this set has therefore been chosen as optimum. It is estimated that a significant improvement in the colour reproduction of certain existing scanners will result from the use of these optimum characteristics, and that their instrumentation can be achieved with only slight loss of signal-to-noise ratio.

Further work is required to ascertain whether or not an improvement (either in colour accuracy or in signal-to-noise ratio) could be achieved if a matrix were used.

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